

Altered metabolism of familial Alzheimer's disease-linked amyloid precursor protein variants in yeast artificial chromosome transgenic mice

Bruce T. Lamb*, Linda M. Call¹, Hilda H. Slunt², Kimberly A. Bardel, Ann M. Lawler¹, Christopher B. Eckman³, Steven G. Younkin³, Greg Holtz⁴, Steven L. Wagner⁴, Donald L. Price², Sangram S. Sisodia² and John D. Gearhart¹

Department of Genetics, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA

¹Developmental Genetics Laboratory, Departments of Gynecology and Obstetrics and Physiology and

²Neuropathology Laboratory, Department of Pathology, The Johns Hopkins University School of Medicine,

Baltimore, MD 21287, USA, ³Mayo Clinic Jacksonville, Jacksonville, FL 32224, USA and ⁴SIBIA Neurosciences, Inc., La Jolla, CA 92037, USA

Received April 15, 1997; Revised and Accepted June 27, 1997

Missense mutations in the β -amyloid precursor protein gene (APP) co-segregate with a small subset of autosomal dominant familial Alzheimer's disease (FAD) cases wherein deposition of the 39–43 amino acid β -amyloid (A β) peptide and neurodegeneration are principal neuropathological hallmarks. To accurately examine the effect of missense mutations on APP metabolism and A β production *in vivo*, we have introduced yeast artificial chromosomes (YACs) containing the entire ~400 kbp human APP gene encoding APP harboring either the asparagine for lysine and leucine for methionine FAD substitution at codons 670 and 671 (APP_{K670N/M671L}), the isoleucine for valine FAD substitution at codon 717 (APP_{V717I}) or a combination of both substitutions into transgenic mice. We demonstrate that, relative to YAC transgenic mice expressing wild-type APP, high levels of A β peptides are detected in the brains of YAC transgenic mice expressing human APP_{K670N/M671L} that is associated with a concomitant diminution in the levels of α -secretase-generated soluble APP derivatives. Moreover, the levels of longer A β peptides (species terminating at amino acids 42/43) are elevated in YAC transgenic mice expressing human APP_{V717I}. These mice should prove valuable for detailed analysis of the *in vivo* effects of the APP FAD mutations in a variety of tissues and throughout aging and for testing therapeutic agents that specifically alter APP metabolism and A β production.

INTRODUCTION

Alzheimer's disease (AD), the most common cause of dementia in the elderly, is a major source of disability and death. Genetic

investigations have identified several etiologies for AD (reviewed in 1), including: a dosage imbalance for chromosome 21, as occurs in Down syndrome (DS); mutations in the β -amyloid precursor protein gene (APP) on chromosome 21, the *presenilin 1* gene on chromosome 14 and the *presenilin 2* gene on chromosome 1 in autosomal dominant early onset familial AD (FAD); inheritance of the *apolipoprotein E4* allele on chromosome 19 as a genetic risk factor for both late onset FAD and sporadic AD. A principal cytological hallmark of all AD cases is parenchymal deposits of β -amyloid (A β), a 39–43 amino acid peptide derived from APP (2).

The APP gene encompasses 18 exons and ~400 kbp of DNA that gives rise to at least four tissue-specific alternatively spliced transcripts that encode proteins of 695, 714, 751 and 770 amino acids (3–7). APP, a type I integral membrane glycoprotein of unknown function, matures through the constitutive secretory pathway and is processed by several pathways, including: cleavage by α -secretase at position 16 of A β , resulting in secretion of the APP ectodomain, thus precluding A β formation; degradation through endosomal–lysosomal pathways; cleavage by β - and γ -secretases at the N- and C-termini of A β respectively, resulting in production and secretion of A β peptides (reviewed in 8). Missense mutations in APP occur in a small subset (<5%) of individuals with early onset FAD. In two large related FAD pedigrees in Sweden (9) a double mutation at codons 670 and 671 (of APP-770) results in substitution of lysine for asparagine and methionine for leucine (APP_{K670N/M671L}). In ~12 FAD pedigrees (10–16) mutations within the transmembrane domain lead to substitutions of either isoleucine, phenylalanine or glycine for valine at residue 717 of APP-770 (APP_{V717I}, APP_{V717F} and APP_{V717G}).

Studies of transfected cells have provided enormous insights into the mechanism(s) whereby the FAD mutations affect APP processing and A β production. For example, cells expressing APP_{K670N/M671L} secrete higher levels of all A β -containing peptides as compared with cells expressing wild-type (wt) APP (17–19); concomitantly, α -secretase-generated soluble APP

*To whom correspondence should be addressed. Tel: +1 216 368 2979; Fax: +1 216 368 3432; Email: blu@po.cwru.edu

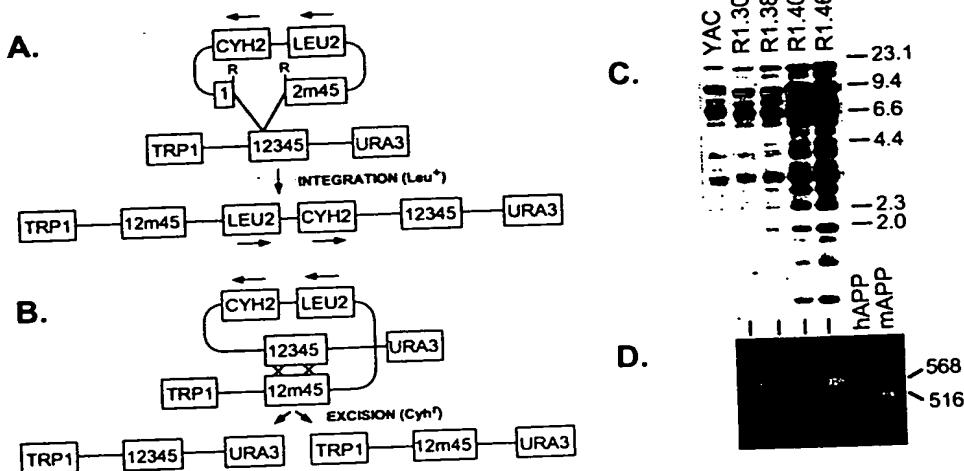


Figure 1. Introduction of mutations into APP YACs and ES cells. (A) A mutation (m) is introduced *in vitro* into a given DNA sequence contained on a YAC (with *TRP1* and *URA3* arms) and cloned into plasmid p680 (30), which contains the yeast *Leu2* and *Cyh2* genes. Cutting the plasmid DNA at a unique site (R) on one side of the mutation as well as introduction of the linear molecule into yeast containing the YAC and selection for *Leu*⁺ transformants result in targeted integration of the plasmid to the corresponding genomic sequence on the YAC. (B) Subsequent selection for *Cyh*⁺ transformants results in excision of the plasmid and generation of the wt or mutated sequence. (C) High molecular weight DNA from a yeast strain containing the APP YAC and four representative ES transformants (see Table 1) were digested with *Hind*III, transferred to nylon membranes and hybridized with a human *Alu* repetitive element (5). On the right are shown the sizes of molecular weight markers in kbp. (D) Cytoplasmic RNA from the ES transformants was subjected to RT-PCR analysis with appropriate mouse (mAPP) and human (hAPP) plasmid cDNA controls (5). On the right are shown the sizes of the expected human (568 bp) and mouse (516 bp) products.

derivatives are diminished (17). In addition, cells expressing the APP₇₁₇ substitutions specifically secrete elevated levels of longer A β peptides (20), extending to residues 42 and/or 43 [A β 1-42(43)]. Evidence that A β 1-42(43) is a highly pathogenic A β species derives from biophysical studies showing the highly fibrillogenic nature of the peptide and immunocytochemical studies of brains of AD and DS individuals, demonstrating that A β 1-42(43) peptides are deposited relatively early in the disease (21-24).

(21–24). Numerous standard transgenic mice have been generated that express various wt and mutant *APP* cDNAs or gene fragments from a variety of promoters (reviewed in 25; see also 26–28). Although these studies have revealed that *APP* transgenic mice can develop age-related A β deposits, they have not specifically and accurately examined the effect of the regulated expression of APP_{K670N/M671L} and APP_{V717I} on the metabolism of *APP* and A β *in vivo*. In contrast, our efforts were designed to introduce the entire ~400 kbp human *APP* gene harboring the FAD mutations into the germline of transgenic mice, thus allowing for the proper spatial and temporal expression of mutant *APP* with appropriate splice donor and acceptor sites needed to generate the entire spectrum of alternatively spliced *APP* transcripts and encoded proteins. A 650 kbp yeast artificial chromosome (YAC) containing the *APP* gene was mutagenized using a homologous recombination strategy in yeast, introduced into mouse embryonic stem (ES) cells by lipid-mediated transfection and finally transferred into the mouse germline. In brain and peripheral tissues of these mutant *APP* YAC transgenic mice high levels of human *APP* mRNA and protein are expressed in a manner that mirrors the spatial and temporal expression pattern of endogenous mouse *APP* gene products. Furthermore, elevated levels of A β peptides are detected in the brains of YAC transgenic mice expressing human APP_{K670N/M671L}, with a concomitant

decrease in levels of soluble α -secretase-generated APP derivatives as compared with mice expressing similar levels of wt APP. Finally, we demonstrate that elevated levels of longer β peptides are detected in YAC transgenic mice expressing human APP $\gamma 711$.

RESULTS

Mutagenesis of *APP* YACs

The APP_{K670N/M671L} and the APP_{V717I} FAD mutations were introduced into a YAC containing the entire wt 400 kb human *APP* gene and ~250 kbp of flanking sequences with multiple neomycin resistance expression cassettes in the YAC vector arm by homologous recombination in yeast (29). Briefly, genomic sequences containing the *APP* exons (16 and 17) to be mutagenized were subcloned by screening an *APP* YAC genomic sub-library with exon-specific PCR products. The mutations in exons 16 (APP_{K670N/M671L}) and 17 (APP_{V717I}) were introduced into the respective genomic fragments using PCR-based mutagenesis strategies and then subcloned into the yeast vector p680. p680 contains the yeast *Leu2* gene, which permits growth in the absence of leucine, and the *Cyh2* gene, which confers sensitivity to cycloheximide (30). Finally, two-step gene replacement was performed in yeast to introduce the mutated *APP* genomic sequences into the 650 kbp *APP* YAC (Fig. 1A and B). YACs containing the mutated *APP* genomic sequences were identified by restriction digestion and sequencing of exon-specific PCR products, while the integrity of the mutant YACs was confirmed by restriction digestion, Southern analysis and pulsed-field gel electrophoresis of yeast genomic DNA (data not shown). Intact YACs were identified containing the APP_{K670N/M671L} and APP_{V717I} FAD mutations separately or both mutations together.

Table 1. Mutant APP YAC ES clones

Colony ^a	Mutation	Expression ^b 5'	Expression ^b 3'	Alu profile ^c	Copy no. ^d	Germline
Py8.9 ^e	Wild-type	+	nd	+	1	Yes
J1.2	K670N/M671L + V717I	+	nd	+	4-5	No
J1.6	K670N/M671L	+	nd	+	1	No
J1.22	K670N/M671L	++	+	+	1	No
J1.38	K670N/M671L + V717I	+++	+++	+	5-6	No
J1.46	V717I	+++	++	+	3-4	No
J1.58	K670N/M671L + V717I	+	+/-	+	2	No
J1.80	V717I	+++	++	+	2	No
J1.88	V717I	+	nd	+	nd	Yes
J1.96	K670N/M671L + V717I	++	++	+	1	Yes
R1.17	K670N/M671L + V717I	++	++	+	6-8	Yes
R1.30	V717I	+++	+++	+	2	Yes
R1.38	V717I	++	+	+	6-8	Yes
R1.40	K670N/M671L	++++	++++	+	6-8	Yes
R1.46	K670N/M671L + V717I	++++	+++	+	12-16	No

^aAn additional 21 J1 and eight R1 ES clones contained a majority of the mutant APP YAC, but were not injected into mouse blastocysts.

^bRelative amounts of APP mRNA as determined by RT-PCR (5).

^cIntactness of Alu repetitive element profile as determined by Southern blot analysis (5).

^dCopy number determined by Southern blot analysis with an APP exon 7 probe that recognizes both mouse and human APP.

^eGenerated in a previous study (5).

Introduction of mutated APP YACs into ES cells and mice

The results of our transfection studies with mutant APP YACs are presented in Table 1. Purified and concentrated mutated APP YAC DNA was introduced into both J1 and R1 ES cells by lipid-mediated transfection of suspension cultures generating 83 and 48 G418^r lines respectively. Twenty one J1 and 13 R1 lines were positive for a majority of the YAC by PCR, including the APP promoter, exon 7, exon 16 and exon 17, and Alu repetitive element PCR (data not shown). The copy number and integrity of the APP YACs in the resulting ES lines (Table 1) was determined by extensive restriction analysis and hybridization with APP (data not shown) and human Alu probes (Fig. 1C) respectively. Integration of YACs containing mutated APP sequences was confirmed by PCR and restriction analysis. Expression of human APP mRNA was determined by reverse transcription-PCR (RT-PCR) analysis (Fig. 1D) with degenerate primers that span the first six exons of mouse/human APP mRNA (5). Several lines were subsequently introduced into mouse blastocysts and numerous chimeras ranging from 10 to 90% ES cell contribution were generated. To date, five separate lines have transmitted ES DNA through the germline.

APP expression in mutant YAC transgenic mice

The expression of human APP was examined in several mutant APP YAC transgenic mice, including line J1.96 (which contains both the APP_{K670N/M671L} and APP_{V717I} mutations) and line R1.40 (which contains only the APP_{K670N/M671L} mutation). RT-PCR analysis with degenerate primers that span the first six exons of mouse/human APP mRNA (5) revealed that the J1.96 line, containing a single copy of the mutant APP YAC, expressed human APP mRNA at levels similar to endogenous mouse *App*

mRNA in brain (Fig. 2, lane 6) and peripheral tissues (Fig. 2; lanes 9, 12 and 15), while line R1.40, containing ~6-8 copies of the mutant APP YAC, expressed human APP mRNA at levels ~2- to 3-fold above endogenous *App* mRNA in all tissues examined (Fig. 2, lanes 7, 10, 13 and 16). Additional RT-PCR experiments (5) with degenerate primers that flank the most common alternatively spliced APP exons (7 and 8) demonstrated that the levels of transcripts that encode human APP-695, -751 and -770 in selected tissues paralleled the levels of alternatively spliced mouse *App* transcripts in all transgenic lines examined (data not shown).

APP processing in mutant YAC transgenic mice

Expression of human APP-related derivatives in brains of mutant APP YAC transgenic mice was examined by Western blot analysis. We demonstrate that in membrane fractions of brains from line J1.96 accumulation of full-length mutant human APP, recognized by antibody CT-15 specific for the terminal 15 amino acids of mouse and human APP (Fig. 3A, lane 3), is essentially indistinguishable from the level of wt human APP (5) in YAC transgenic line Py8.9 (Fig. 3A, lane 2). However, the levels of an ~13.5 kDa fragment that likely represents a β -secretase generated C-terminal peptide extending from the N-terminus of A β to the end of the APP cytoplasmic tail is slightly elevated in membrane fractions of the J1.96 line (Fig. 3B, lane 3) relative to brains of animals expressing wt human APP (Fig. 3B, lane 2), whereas an ~12 kDa fragment that likely represents the α -secretase-generated C-terminal fragment remains unchanged.

These data are consistent with our earlier demonstration that cultured cells expressing APP_{K670N/M671L} accumulate elevated levels of a C-terminal ~13.5 kDa fragment generated following cleavage by β -secretase (17). Reinforcing this view, we also

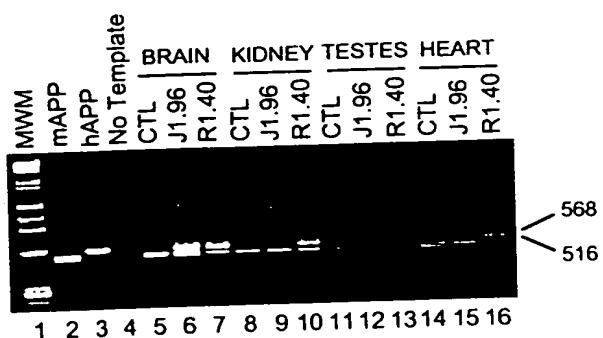


Figure 2. Analysis of APP mRNA expression in mutant APP YAC transgenic mice. Total RNA from the brain (lanes 5–7), kidney (lanes 8–10), testes (lanes 11–13) and heart (lanes 14–16) of a 2-month-old control mouse (CTL), a mouse from line J1.96 (containing both the APP_{K670N/M671} and APP_{V717I} mutations) and a mouse from line R1.40 (containing the APP_{K670N/M671} mutation) was subjected to RT-PCR analysis with appropriate mouse (mAPP), human (hAPP) and no template controls (lanes 1–3). Because the sense primer is ³²P-labeled in these experiments, the gel was dried and bands quantitated by phosphorimaging technology. Line J1.96 produces roughly equivalent amounts of mouse and human APP mRNA in the brain, while line R1.40 produces ~3-fold higher levels of human APP mRNA relative to mouse *App* mRNA. On the right are shown the sizes of the expected human (568 bp) and mouse (516 bp) products.

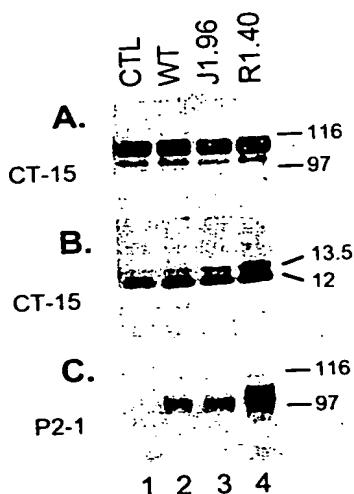


Figure 3. Soluble and cell-associated APP-derived molecules in APP YAC transgenic mouse brain. Soluble (S2 fraction) and cell-associated (P2 fraction) protein extracts from the brains of 3-month-old control (CTL; lane 1), wild-type (WT, line Py8.9; lane 2) and mutant (line J1.96, containing both APP_{K670N/M671} and APP_{V717I} mutations, and line R1.40, containing the APP_{K670N/M671} mutation; lanes 3 and 4) APP YAC transgenic mice (5) were subjected to Western blot analysis (17,36). P2 extracts subjected to SDS-PAGE (A) and Tris-Tricine-PAGE (B) were visualized with antibody CT-15 (recognizing the C-terminal 15 amino acids of mouse and human APP), while S2 extracts (C) subjected to SDS-PAGE were visualized with antibody p2-1 (recognizing an epitope in the N-terminus of human APP). On the right are shown the approximate sizes in kDa.

document that the amount of the same β -secretase-generated fragment accumulates to very high levels in line R1.40 mice overexpressing high levels of human APP_{K670N/M671} (Fig. 3B,

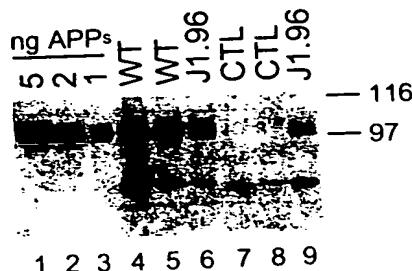


Figure 4. Levels of α -secretase-cleaved APP in mutant APP YAC transgenic mouse brain. Soluble (S2 fraction) extracts from the brains of 4-month-old control (CTL; lanes 7 and 8), wild-type (WT, line Py8.9; lanes 4 and 5) and mutant (line J1.96, containing both APP_{K670N/M671} and APP_{V717I} mutations; lanes 6 and 9) APP YAC transgenic mice (5) and α -secretase-cleaved APP standards (lanes 1–3) were subjected to Western blot analysis. Parallel blots were visualized with antibody 6E10 (recognizing α -secretase cleaved human APP; 32) and a horseradish peroxidase tagged antibody (data not shown) against full-length APP. Blots quantified with ¹²⁵I-labeled protein A revealed an ~40–50% reduction in α -secretase-cleaved products in mutant line J1.96 relative to wt when normalized to the full-length APP signal. On the right are shown the approximate sizes of the molecular weight markers in kDa.

lane 4). Interestingly, the steady-state levels of full-length human APP in line R1.40 (Fig. 3A, lane 4) is ~3-fold higher than endogenous *App* (Fig. 3A, lane 1), a finding that parallels the RT-PCR studies shown in Figure 2.

Analysis of soluble APP derivatives (APP^s) in brains of mutant APP line J1.96 (Fig. 3C, lane 3) and wt APP line Py8.9 (Fig. 3C, lane 2) using an antibody specific for epitopes in the N-terminus of human APP failed to reveal a significant difference in total APP^s between these lines. However, commensurate with an elevation of β -secretase-generated C-terminal fragments in the brain of line R1.40, we observed elevated levels of accumulated APP^s (Fig. 3C, lane 4). We extended this analysis to examine the levels of α -secretase-generated soluble derivatives in lines J1.96 and Py8.9, expressing essentially identical levels of mutant and wt human APP respectively. Western blot analysis of soluble fractions (S2) from brains revealed an ~50% decrease in the steady-state levels of α -secretase-generated human APP^s derivatives in the J1.96 line relative to line Py8.9 (Fig. 4), this despite our demonstration that the total levels of APP^s appeared unchanged between the mutant and wt transgenic lines (Fig. 3C).

Although decreased α -secretase processing of mutant APP_{K670N/M671} appears surprising, these data are fully consistent with our earlier cellular transfection studies which documented that one effect of the APP_{K670N/M671} mutation is to enhance cleavage at the β -secretase site in the Golgi compartment (17). As a result, a fraction of APP molecules which would normally be cleared by α -secretase at the plasma membrane would be effectively disabled by the prior action of β -secretase. Hence, in the medium of cells expressing APP_{K670N/M671} the level of α -secretase derivatives are considerably diminished relative to the medium of cells expressing similar levels of wt APP.

A β production in mutant APP YAC transgenic mice

Levels of A β were quantified using sandwich enzyme-linked immunosorbent assays (ELISAs) (20). Analysis of brain homogenates demonstrated an increase both in the amount of

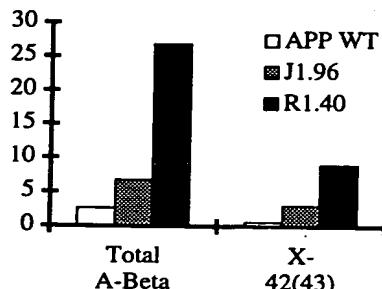


Figure 5. Levels of various A β peptides in APP YAC transgenic mouse brain. Brain extracts from a 3-month-old control, wild-type (WT, line Py8.9) and mutant (line J1.96, containing both the APP $K670N/M671$ and APP $V717I$ mutations, and line R1.40, containing the APP $K670N/M671$ mutation) APP YAC transgenic mice (5) were subjected to a sensitive sandwich ELISA that detects the various A β peptides [shown are total A β and A β X-42(43)]. Levels are expressed as pmol/g relative to control standardized peptides.

total soluble A β and the proportion of longer A β 1-42(43) in the mutant APP J1.96 line compared with the wt APP line Py8.9 (Fig. 5, A β X-42(43) is 40% of total A β in line J1.96 compared with 20% for line Py8.9). Moreover, a dramatic increase in both total A β and A β 1-42(43) species was observed in line R1.40. Our preliminary studies of [35 S]methionine-labeled primary cortical neuronal cultures and immunoprecipitation of A β from conditioned medium revealed a substantial increase in A β in the mutant APP line J1.96 relative to wt APP line Py8.9 or control cultures (data not shown). These *in vivo* results, similar to those obtained in cell culture experiments and human plasma, suggest that the effect of the APP $K670N/M671$ L FAD mutation is to enhance β -secretase cleavage, resulting in increased production and secretion of A β , while the APP $V717I$ mutation appears to influence processing at the γ -secretase site in a manner that elevates the levels of secreted A β 1-42(43).

DISCUSSION

A β , the principal component of parenchymal amyloid deposits in AD, is derived from the integral membrane glycoprotein APP. Several mutations have been identified in the APP gene that co-segregate with affected individuals in FAD pedigrees (reviewed in 1). Although multiple APP transgenic mice have been generated in attempts to develop animal models of AD (reviewed in 25; see also 26-28), the molecular mechanisms involved in altered APP metabolism and A β deposition in individuals with FAD-linked mutations in APP have not been fully clarified. The present report provides insight into the effects of the APP $K670N/M671$ L and APP $V717I$ FAD mutations on APP metabolism and A β production in an *in vivo* setting that mimics the conditions occurring in individuals with the FAD mutations. We have generated lines of transgenic mice that contain the entire human APP gene carried on a 650 kbp YAC with the APP $K670N/M671$ L mutation, the APP $V717I$ mutation or both mutations together. In these mice mutant human APP transcripts and protein(s) are expressed in spatial and temporal patterns similar to the endogenous mouse products in both brain and peripheral tissues. Western blot analysis and sensitive ELISAs of whole brain homogenates demonstrated that in mice expressing APP $K670N/M671$ L cell-associated C-terminal APP fragments

containing the A β domain and A β peptides were elevated concomitant with a reduction in the levels of release of α -secretase-cleaved APP products. Mice expressing APP $V717I$, on the other hand, accumulated elevated levels of longer A β 1-42(43) species in the brain.

One additional consideration in these YAC transgenic experiments is the presence of an additional gene(s) carried on the APP YAC that might alter the effect of the FAD mutations when expressed at dosage imbalance. Initial experiments with exon trapping from the 650 kbp APP YAC revealed the presence of five additional exons that do not encode for APP (J.J. Yeh, B.T. Lamb and J.D. Gearhart, unpublished observations). While four of these exons did not reveal substantial identity with sequences in the database, one trapped exon of 103 nt revealed complete identity with bp 167-269 (exon 2) and amino acid residues 1-25 of the human transcription factor GABPA (E4TF1-60) gene (GenBank accession no. D13318), consistent with the localization of this gene to chromosome 21q21.2 (31,32). This transcription factor contains an ets-related DNA binding domain which binds to DNA at CGGAAA/G sequences and forms heterodimers with other polypeptides (33). Although it remains unclear whether the entire GABPA gene is present on the 650 kbp APP YAC, the biochemical abnormalities observed in the mutant APP YAC transgenic mice likely reflect a property unique to the mutant APP polypeptide and not dosage imbalance for GABPA, as we have generated both wt and mutant APP YAC transgenic mice that express APP at a similar level (i.e. wt line Py8.9 and mutant line J1.96).

In summary, our results suggest that *in vivo* both FAD mutations influence APP processing in a manner leading to increased levels of the highly amyloidogenic peptide A β 1-42(43); mice expressing APP $K670N/M671$ accumulate increased levels of all A β peptides, while mice expressing APP $V717I$ selectively accumulate elevated levels of A β 1-42(43). In view of *in vitro* aggregation and immunocytochemical studies which have suggested that A β 1-42(43) is highly amyloidogenic and deposited early in the disease process, we are enthusiastic that the APP YAC mice described herein will develop amyloid deposits and associated lesions, as has been described in mice expressing other FAD-linked APP transgenes (26-28). In addition, these YAC transgenic mice will allow an accurate examination of the effects of the FAD mutations on APP processing in a variety of cell types (neurons, astrocytes, glia, blood vessels, etc.) as well as on alterations in neuronal physiology and behavior throughout aging. Finally, our results suggest that the YAC transgenic strategy will allow the stringent testing of the roles of the early onset *presenilin* FAD mutations in amyloidogenesis and examine the potential interactive effects of the different early onset FAD gene mutations.

MATERIALS AND METHODS

YAC manipulations

A human APP genomic sub-library was constructed by pulsed-field gel electrophoresis fractionation and isolation of the 650 kbp APP YAC, followed by digestion with *Sac*I and ligation into *Sac*I-digested λ phage ZAPII (Stratagene). Exon 16 and 17 APP genomic clones were isolated by screening the sub-library with a 229 bp exon 16 (9) and a 319 bp exon 17 product (13), yielding 4.2 and 3.5 kbp genomic clones respectively. Clones

were converted to plasmids and restriction maps generated. A 1.8 kbp *Hind*III fragment containing exon 16 and a 3 kbp *Eco*RI fragment containing exon 17 were subcloned into Bluescript (Stratagene). The APP_{K670N/M671} and APP_{V717I} mutations were introduced into exon 16 and 17 genomic subclones respectively by PCR mutagenesis. Primary PCR was performed with the internal mutagenic primers 5'-GAGATCTCTGAAGTGAATC-TGGATGCAGAATTCCGAC-3' and its complement for the APP_{K670N/M671} mutation and 5'-GGACAGTGATCATCATCAC-3' and its complement for the APP_{V717I} mutation, along with external vector primers. Secondary PCR was performed with the external primers alone, products subcloned into the yeast recombination plasmid p680 (provided by P.Hieter, Johns Hopkins Medical Institutions) and the presence of the mutations confirmed by DNA sequencing. An *Acc*I site upstream of the exon 17 genomic clone was converted to a *Stu*I site by the addition of linkers.

of linkers. Plasmids containing the mutagenized sequences were linearized with *Stu*I, which cuts upstream of both exon 16 and 17, and introduced into the wt *APP* YAC by two-step gene replacement in yeast as described (30). The presence of the mutations was determined by restriction digestion of exon-specific PCR products and confirmed by DNA sequencing and Southern blot analysis. Mutated YAC DNA was purified essentially as described (5) with a second dimension electrophoresis step in 4% Nu-Sieve low melting point agarose (FMC) to concentrate the YAC DNA (34).

Cell culture and blastocyst injections

J1 (kindly provided by R.Jaenisch, The Whitehead Institute) and R1 (kindly provided by J.Rossant, Univcrsity of Toronto) ES cells were maintained by standard techniques, grown on mitotically inactivated neo^r primary embryonic fibroblasts in the presence of leukemia inhibitory factor. For transfection, 1 ml isolated YAC DNA was gently mixed with 50 µg lipofectin (BRL) in polystyrene tubes and allowed to complex for 45 min at room temperature. Lipid-DNA complexes were added to 5×10^6 ES cells, resuspended in 9 ml OptiMEM (BRL), placed on 10 cm bacterial dishes, incubated for 4 h at 37°C and then plated onto 10 cm tissue culture dishes with feeders. G418 (250 µg/ml) selection was initiated the following day and continued for 11 days. Injection of dissociated ES cells into C57BL/6J blastocysts and matings of the resultant chimeras were carried out essentially as described (35). Genomic DNA was isolated from ES cells and mouse tails and analyzed by PCR or by Southern blot with a variety of probes as previously described (5).

RNA and protein analysis

RNA was isolated from ES cells and mouse tissues and RT-PCR was performed for the first six exons or across the alternatively spliced exons of mouse/human APP as described previously (5). Protein extracts and immunoblots were prepared as described (17,36). Sandwich ELISAs specific for A β 1-40 versus A β 1-42(43) were performed as described (20).

ACKNOWLEDGEMENTS

We thank Q.Boese and S.Chideya for expert technical assistance, G.Thinakaran for assistance with the protein analysis, P.Hieter and C.Connelly for assistance with yeast technology and H.Willard for critical reading of the manuscript. This work was supported by National Institutes of Health grants AG05146 and NS20471 (S.S.S. and D.L.P.), HD24605 (J.D.G.) and AG14451 (B.T.L.). D.L.P. is the recipient of a Javitz Neuroscience Investigator Award (NIH NS10580) and a Leadership and Excellence in Alzheimer's Disease (LEAD) Award (NIH AG07914). S.S.S. is the recipient of an Alzheimer's Association Zenith Award.

ABBREVIATIONS

$\text{A}\beta$, β -amyloid; $\text{A}\beta 1-42(43)$, $\text{A}\beta$ extending to residue 42 or 43; AD, Alzheimer's disease; APP, amyloid precursor protein; APPs, soluble APP derivatives; APP_{K670N/M671L}, APP with asparagine for lysine and leucine for methionine substitution at codons 670/671; APP_{V717I}, APP with isoleucine for valine substitution at codon 717; ES, embryonic stem; FAD, familial Alzheimer's disease; wt, wild-type; YAC, yeast artificial chromosome.

REFERENCES

1. Tanzi,R.E., Kovacs,D.M., Kim,T.-W., Moir,R.D., Guenette,S.Y. and Wasco,W. (1996) The gene defects responsible for familial Alzheimer's disease. *Neurobiol. Dis.*, 3, 159-168.
2. Kang,J., Lemaire,H.G., Unterbeck,A., Salbaum,J.M., Masters,C.L., Grzeschik,K.H., Miltzhaup,G., Beyreuther,K. and Muller,H.B. (1987) The precursor of Alzheimer's disease amyloid A4 protein resembles a cell-surface receptor. *Nature*, 325, 733-736.
3. Golde,T.E., Estus,S., Usiak,M., Younkin,L.H. and Younkin,S.G. (1990) Expression of β amyloid protein precursor mRNAs: recognition of a novel alternatively spliced form and quantitation in Alzheimer's disease using PCR. *Neuron*, 4, 253-267.
4. Kitaguchi,N., Takahashi,Y., Tokushima,Y., Shiojiri,S. and Ito,H. (1988) Novel precursor of Alzheimer's disease amyloid protein shows protease inhibitory activity. *Nature*, 331, 530-532.
5. Lamb,B.T., Sisodia,S.S., Lawler,A.M., Slunt,H.H., Kitt,C.A., Kearns,W.G., Pearson,P.L., Price,D.L. and Gearhart,J.D. (1993) Introduction and expression of the 400 kilobase *amyloid precursor protein* gene in transgenic mice. *Nature Genet.*, 5, 22-30.
6. Ponte,P., Gonzalez,D.P., Schilling,J., Miller,J., Hsu,D., Greenberg,B., Davis,K., Wallace,W., Lieberburg,I. and Fuller,F. (1988) A new A4 amyloid mRNA contains a domain homologous to serine proteinase inhibitors. *Nature*, 331, 525-527.
7. Tanzi,R.E., McClatchey,A.I., Lamperti,E.D., Villa,K.L., Gusella,J.F. and Neve,R.L. (1988) Protease inhibitor domain encoded by an amyloid protein precursor mRNA associated with Alzheimer's disease. *Nature*, 331, 528-530.
8. Selkoe,D.J. (1994) Cell biology of the amyloid beta-protein precursor and the mechanism of Alzheimer's disease. *Annu. Rev. Cell Biol.*, 10, 373-403.
9. Mullan,M., Crawford,F., Axelman,K., Houlden,H., Lilius,L., Winblad,B. and Lannfelt,L. (1992) A pathogenetic mutation for probable Alzheimer's disease in the APP gene at the N-terminus of β -amyloid. *Nature Genet.*, 1, 345-347.
10. Brooks,W.S., Martins,R.N., De Voecht,J., Nicholson,G.A., Schofield,P.R., Kwok,J.B., Fisher,C., Yeung,L.U. and Van Broeckhoven,C. (1995) A mutation in codon 717 of the amyloid precursor protein gene in an Australian family with Alzheimer's disease. *Neurosci. Lett.*, 199, 183-196.
11. Chartier-Harlin,M.C., Crawford,F., Houlden,H., Warren,A., Hughes,D., Fidani,L., Goate,A., Rossor,M., Roques,P., Hardy,J. and Mullan,M. (1991) Early-onset Alzheimer's disease caused by mutations at codon 717 of the β -amyloid precursor protein gene. *Nature*, 353, 844-846.

12. Fidani,L., Rooke,K., Chartier-Harlin,M.-C., Hughes,D., Tanzi,R., Mullan,M., Roques,P., Rossor,M., Hardy,J. and Goate,A. (1992) Screening for mutations in the open reading frame and promoter of the β -amyloid precursor protein gene in familial Alzheimer's disease: identification of a further family with APP717 Val-Ile. *Hum. Mol. Genet.*, **1**, 165–168.
13. Goate,A., Chartier-Harlin,M.-C., Mullan,M., Brown,J., Crawford,F., Fidani,L., Giuffra,L., Haynes,A., Irving,N., James,L., Mant,R., Newton,P., Rooke,K., Roques,P., Talbot,C., Perciak-Vance,M., Roses,A., Williamson,R., Rossor,M., Owen,M. and Hardy,J. (1991) Segregation of a missense mutation in the amyloid precursor protein gene with familial Alzheimer's disease. *Nature*, **349**, 704–706.
14. Murrell,J., Farlow,M., Ghetti,B. and Benson,M.D. (1991) A mutation in the amyloid precursor protein associated with hereditary Alzheimer's disease. *Science*, **254**, 97–99.
15. Naruse,S., Igarashi,S., Aoki,K., Kaneko,K., Iihara,K., Miyatake,T., Kobayashi,H., Inuzuka,T., Shimizu,T., Kojima,T. and Tsuji,S. (1991) Mis-sense mutation val-ile in exon-17 of amyloid precursor protein gene in Japanese familial Alzheimer's disease. *Lancet*, **337**, 978–979.
16. Vanduijn,C.M., Hendriks,L., Cruts,M., Hardy,J.A., Hofman,A. and Van Broeckhoven,C. (1991) Amyloid precursor protein gene mutation in early-onset Alzheimer's disease. *Lancet*, **337**, 978.
17. Thinakaran,G., Teplow,D.B., Siman,R., Greenberg,B. and Sisodia,S.S. (1996) Metabolism of the 'Swedish' amyloid precursor protein variant in Neuro2a (N2a) cells. *J. Biol. Chem.*, **271**, 9390–9397.
18. Citron,M., Oltersdorf,T., Haass,C., McConlogue,L., Hung,A.Y., Seubert,P., Vigo-Pelletier,C., Lieberburg,I. and Selkoe,D.J. (1992) Mutations of the β -amyloid precursor protein in familial Alzheimer's disease increase β -protein production. *Nature*, **360**, 672–674.
19. Cai,X.-D., Golde,T.E. and Younkin,S.G. (1993) Release of excess amyloid β protein from a mutant amyloid β protein precursor. *Science*, **259**, 514–516.
20. Suzuki,N., Cheung,T.T., Cai,X.-D., Odaka,A., Otvos,L., Eckman,C., Golde,T.E. and Younkin,S.G. (1994) An increased percentage of long amyloid β protein secreted by familial amyloid β protein precursor (APP717) mutants. *Science*, **264**, 1336–1340.
21. Iwatsubo,T., Odaka,A., Suzuki,N., Nizusawa,H., Nukina,N. and Ihara,Y. (1994) Visualization of A β 42(43)-positive and A β 40-positive senile plaques with end-specific A β -monoclonal antibodies: evidence that an initially deposited A β species is A β 1–42(43). *Neuron*, **13**, 45–53.
22. Jarrett,J.T. and Lansbury,P.T.J. (1993) Seeding 'one-dimensional crystallization' of amyloid: a pathogenic mechanism in Alzheimer's disease and scrapie? *Cell*, **73**, 1055–1058.
23. Jarrett,J.T., Berger,E.P. and Lansbury,P.T. (1993) The carboxy terminus of the β -amyloid protein is critical for the seeding of amyloid formation: implications for the pathogenesis of Alzheimer's disease. *Biochemistry*, **32**, 4693–4697.
24. Tamaoka,A., Odaka,A., Ishibashi,Y., Usami,M., Sahara,N., Suzuki,N., Nukina,N., Mizusawa,H., Shoji,S., Kanazawa,I. and Mori,H. (1994) APP717 missense mutation affects the ratio of amyloid β protein species (A β 1–42/43 and A β 1–40) in familial Alzheimer's disease brain. *J. Biol. Chem.*, **269**, 32721–32724.
25. Lamb,B.T. (1995) Making models for Alzheimer's disease. *Nature Genet.*, **9**, 4–6.
26. Nalbantoglu,J., Tirado-Santiago,G., Lahsaini,A., Poirier,J., Goncalves,O., Verge,G., Momoli,F., Weiner,S.A., Massicotte,G., Julien,J.-P. and Shapiro,M.L. (1997) Impaired learning and LTP in mice expressing the carboxy terminus of the Alzheimer amyloid precursor protein. *Nature*, **387**, 500–505.
27. Hsiao,K., Chapman,P., Nilsen,S., Eckman,C., Harigaya,Y., Yang,F. and Cole,G. (1996) Correlative memory deficits, A β elevation and amyloid plaques in transgenic mice. *Science*, **274**, 99–102.
28. Games,D., Adams,D., Alessandrini,R., Barbour,R., Berthelette,P., Blackwell,C., Carr,T., Clemens,J., Donaldson,T., Gillespie,F., Guido,T., Hagopian,S., Johnson-Wood,K., Khan,K., Lee,M., Leibowitz,P., Lieberburg,I., Little,S., Masliah,E., McConlogue,L., Montoya-Zavalva,M., Mucke,L., Paganini,L., Penniman,E., Power,M., Schenk,D., Seubert,P., Snyder,B., Soriano,F., Tan,H., Vitale,J., Wadsworth,S., Wolozin,B. and Zhao,J. (1995) Alzheimer-type neuropathology in transgenic mice overexpressing V717F β -amyloid precursor protein. *Nature*, **373**, 523–527.
29. Heiter,P., Connelly,C., Sheri,J., McCormick,M.K., Antonarakis,S., Pavan,W. and Reeves,R. (1990) Yeast artificial chromosomes: promises kept and pending. In Davies,K.E. and Tilghman,S. (eds), *Genome Analysis*, Vol. I, *Genetic and Physical Mapping*. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY, pp. 83–120.
30. Ketner,G., Spencer,F., Tugendreich,S., Connelly,C. and Heiter,P. (1994) Efficient manipulation of the human adenovirus genome as an infectious yeast artificial chromosome clone. *Proc. Natl. Acad. Sci. USA*, **91**, 6186–6190.
31. Goto,M., Shimizu,T., Sawada,J.-I., Sawa,C., Watanabe,H., Ichikawa,H., Ohira,M., Ohki,M. and Handa,H. (1995) Assignment of the E4TF1-60 gene to human chromosome 21q21.2-q21.3. *Gene*, **166**, 337–338.
32. Chrast,R., Chen,H., Morris,M.A. and Antonarakis,S.E. (1995) Mapping of the human transcription factor GABPA (E4TF-1) gene to chromosome 21. *Genomics*, **28**, 119–122.
33. Watanabe,H., Sawada,J.-I., Yano,K.-I., Yamaguchi,K., Goto,M. and Handa,H. (1993) cDNA cloning of transcription factor E4TF1 subunits with ets and notch motifs. *Mol. Cell. Biol.*, **13**, 1385–1391.
34. Schedl,A., Larin,Z., Montoliu,L., Thies,E., Kelsey,G., Lehrach,H. and SchYtz,G. (1993) A method for the generation of YAC transgenic mice by pronuclear microinjection. *Nucleic Acids Res.*, **21**, 4783–4787.
35. Bradley,A. (1987) Production and analysis of chimeric mice. In Robertson,E.J. (ed.), *Teratocarcinomas and Embryonic Stem Cells: A Practical Approach*. IRL Press, Oxford, UK, pp. 113–151.
36. Blackstone,C.D., Moss,S.J., Martin,L.J., Levey,A.I., Price,D.L. and Huganir,R.L. (1992) Biochemical characterization and localization of a non-N-methyl-D-aspartate glutamate receptor in rat brain. *J. Neurochem.*, **58**, 1118–1126.
37. Hattori,M., Tsukahara,F., Furuhata,Y., Tanahashi,H., Hirose,M., Saito,M., Tsukuni,S. and Sakaki,Y. (1997) A novel method for making nested deletions and its application for sequencing of a 300 kb region of human APP locus. *Nucleic Acids Res.*, **25**, 1802–1808.

NOTE ADDED IN PROOF

Recently, the entire human APP gene was sequenced (37) and found to consist of 286 722 bp, considerably smaller than previous size estimates (5). Analysis of the resulting genomic sequence should provide considerable information with regards to additional expressed sequences and/or genes surrounding the APP locus.